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**Linder**

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(54) **AUTOMATIC SUB-MILLISECOND CLOCK SYNCHRONIZATION**

(58) **Field of Classification Search**  
CPC ..... G01R 31/26; G01R 31/2642; G01R 31/2648; G01R 31/2831; G01R 31/31702; G01R 1/20; G01R 1/22

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(Continued)

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(57) **ABSTRACT**

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According to one aspect, embodiments of the invention provide a system for monitoring a plurality of circuit branches coupled to an input line, the system comprising a communication bus, a controller having a primary clock with a first clock value and configured to sample voltage on the input line based on the first clock value, a plurality of sensor circuits, each sensor circuit having a secondary clock with a second clock value and configured to sample current in the at least one of the plurality of circuit branches based on the second clock value, and wherein the controller is further configured to initiate, via the communication bus, synchronization of at least one secondary clock and the primary clock, and to synchronize, via the communication bus, the at least one secondary clock and the primary clock

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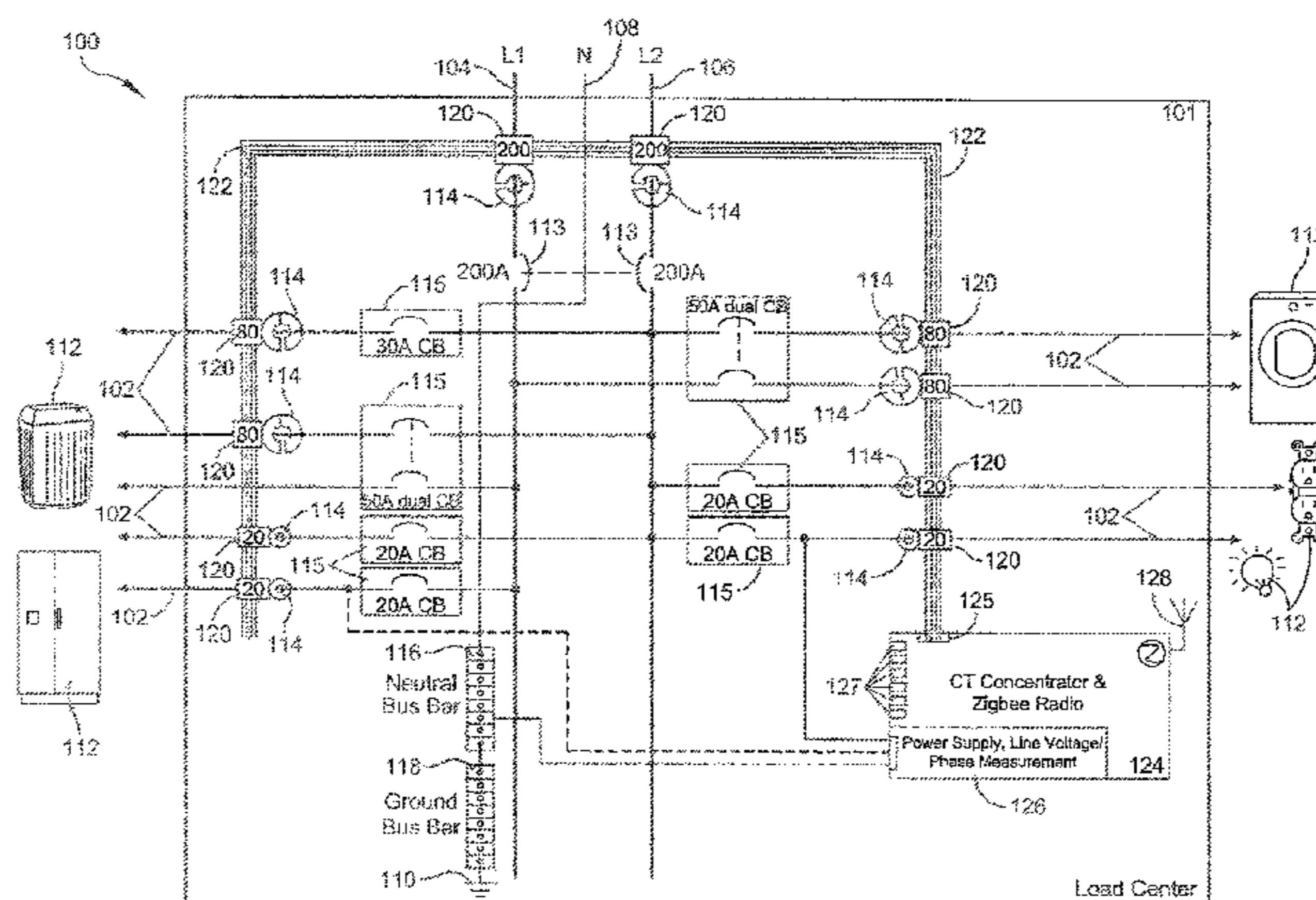
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to account for transmission latency in the communication bus.

**19 Claims, 7 Drawing Sheets**

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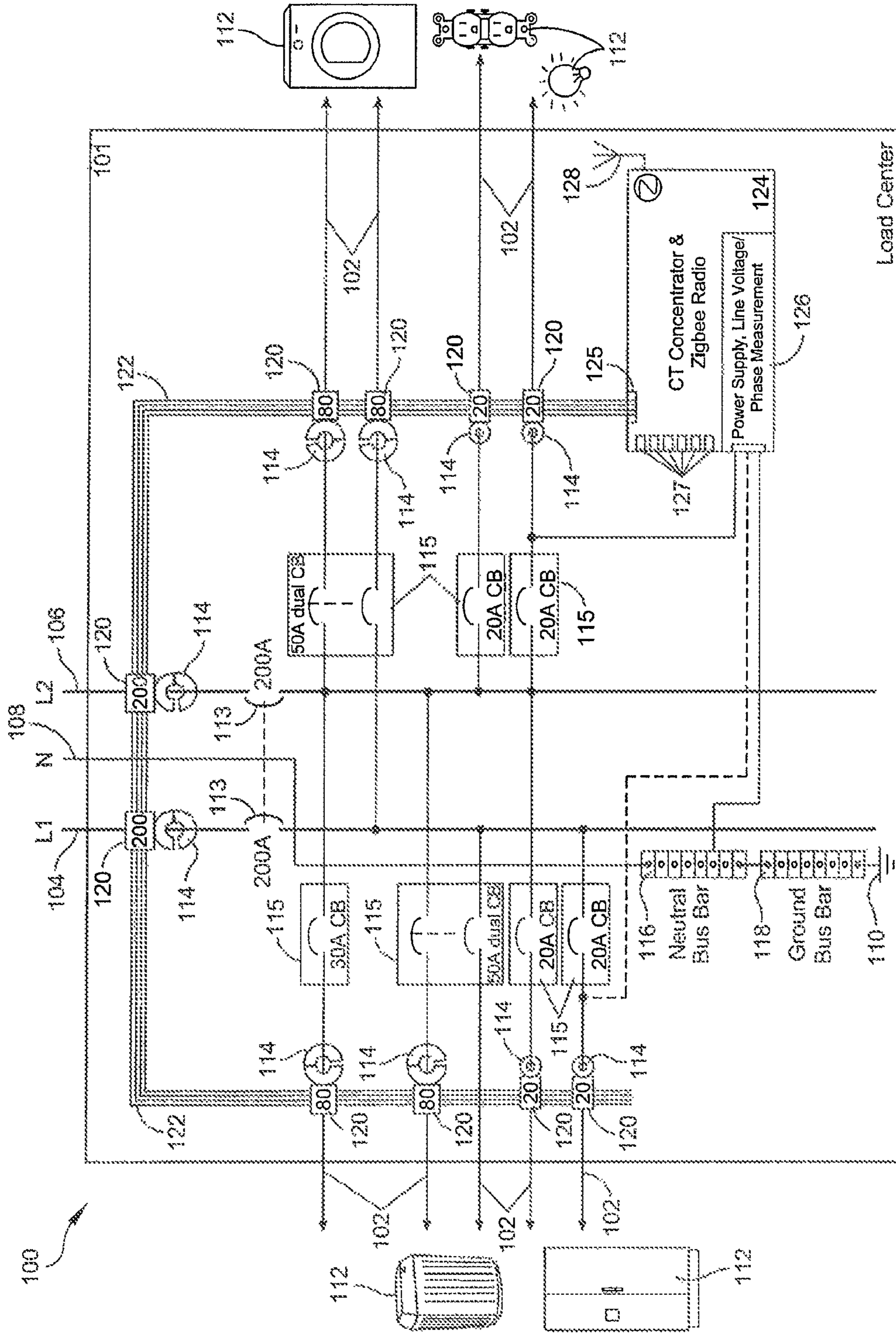


FIG. 1

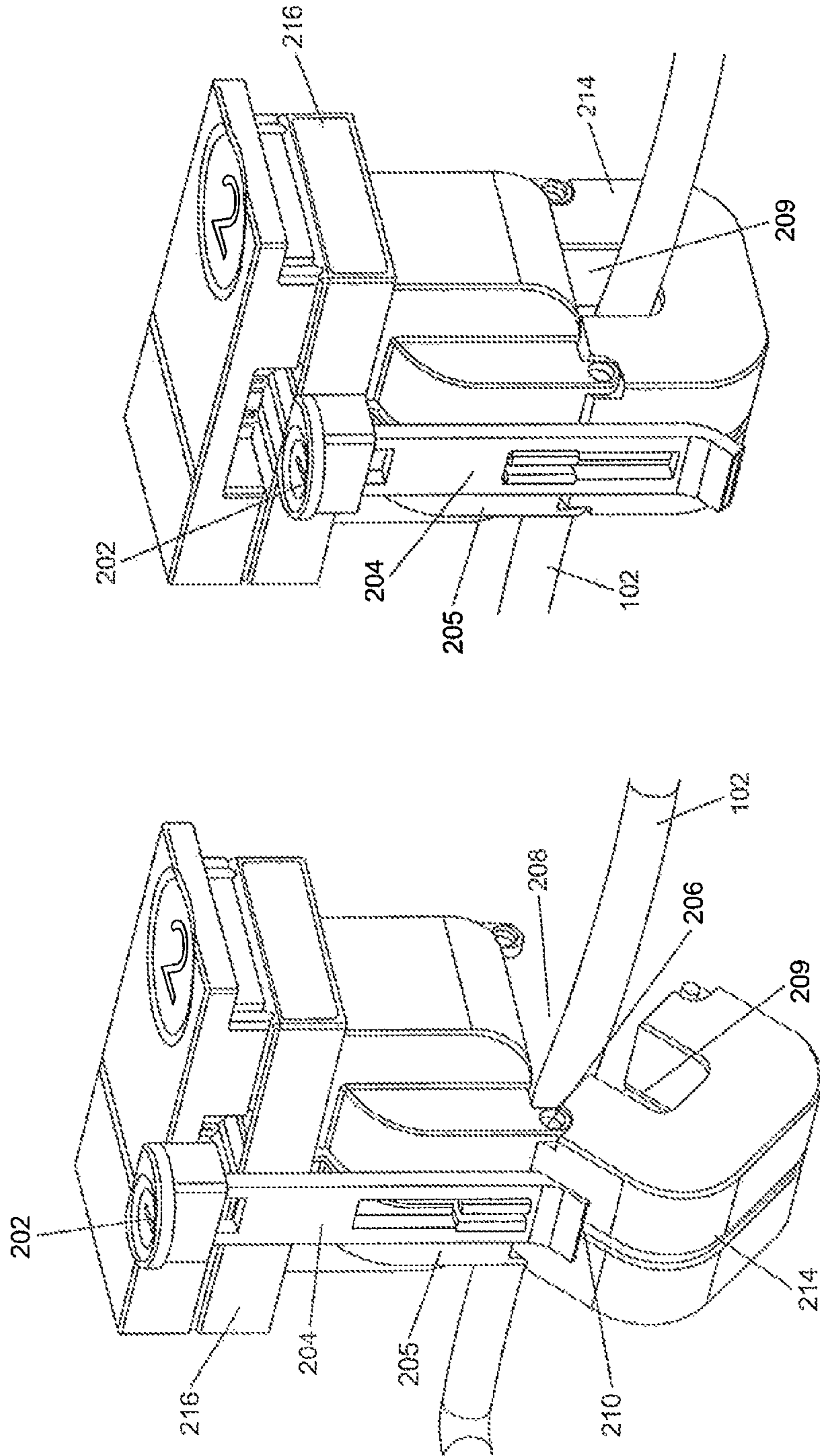


FIG. 2B

FIG. 2A



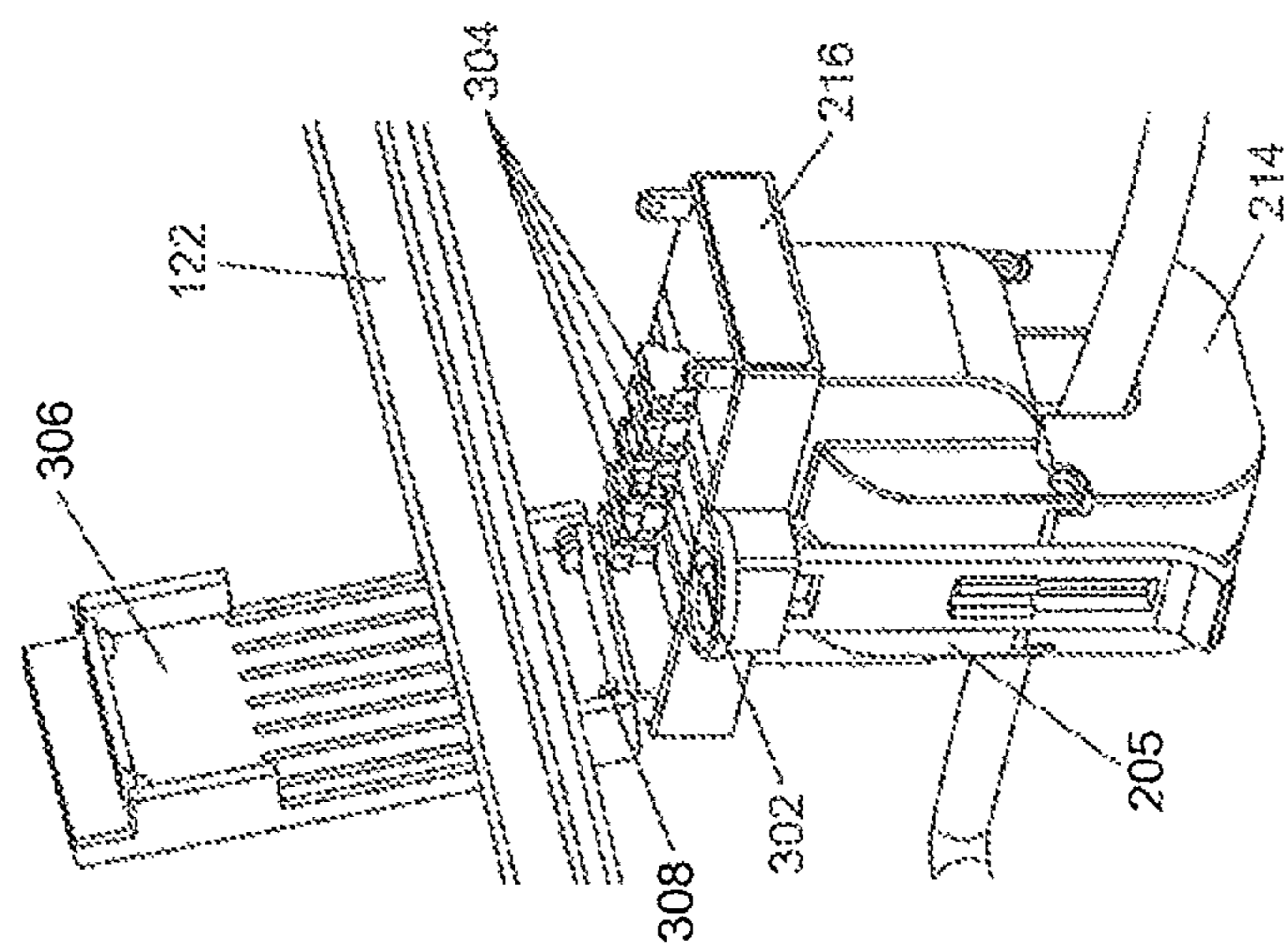


FIG. 3A

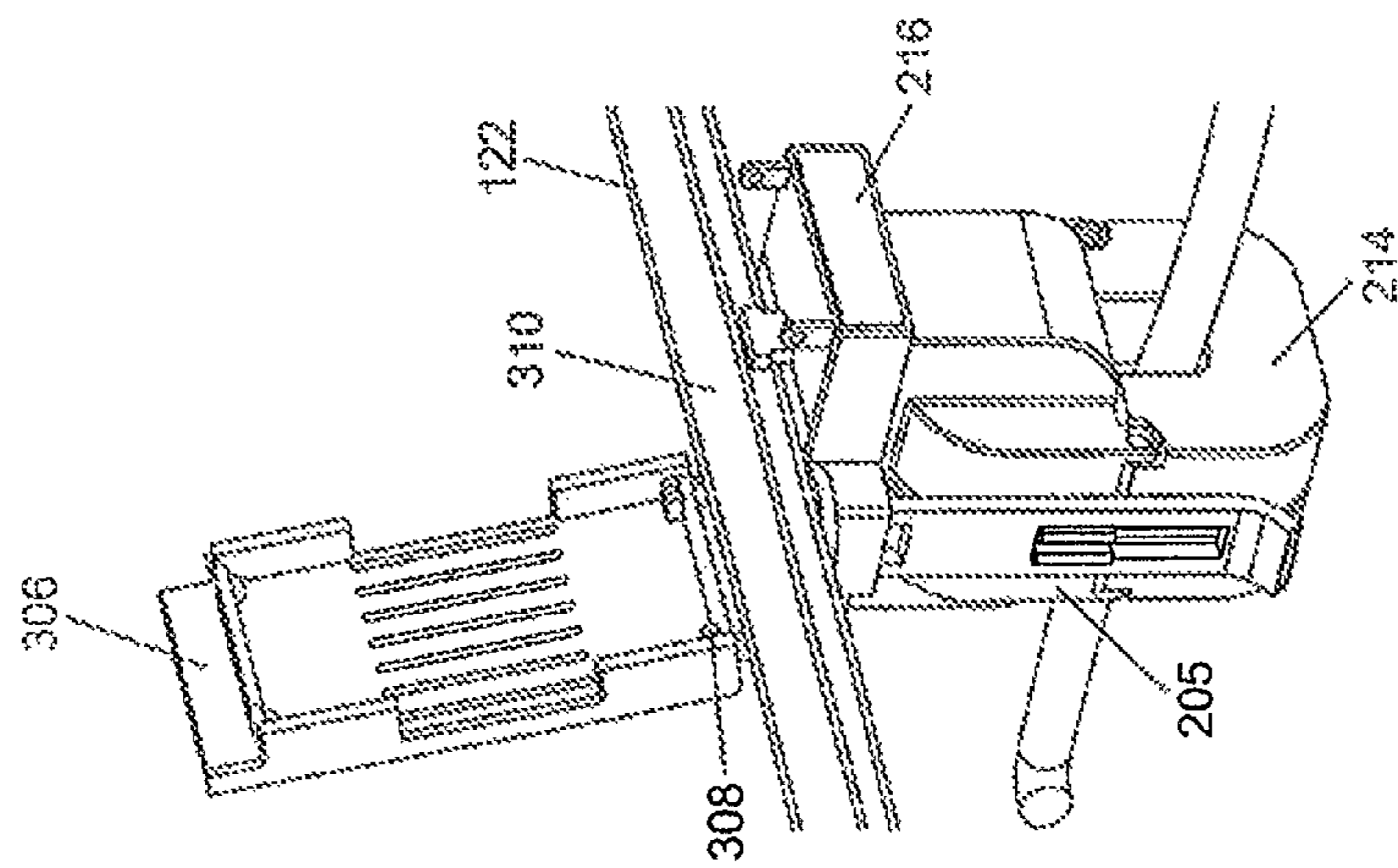


FIG. 3B

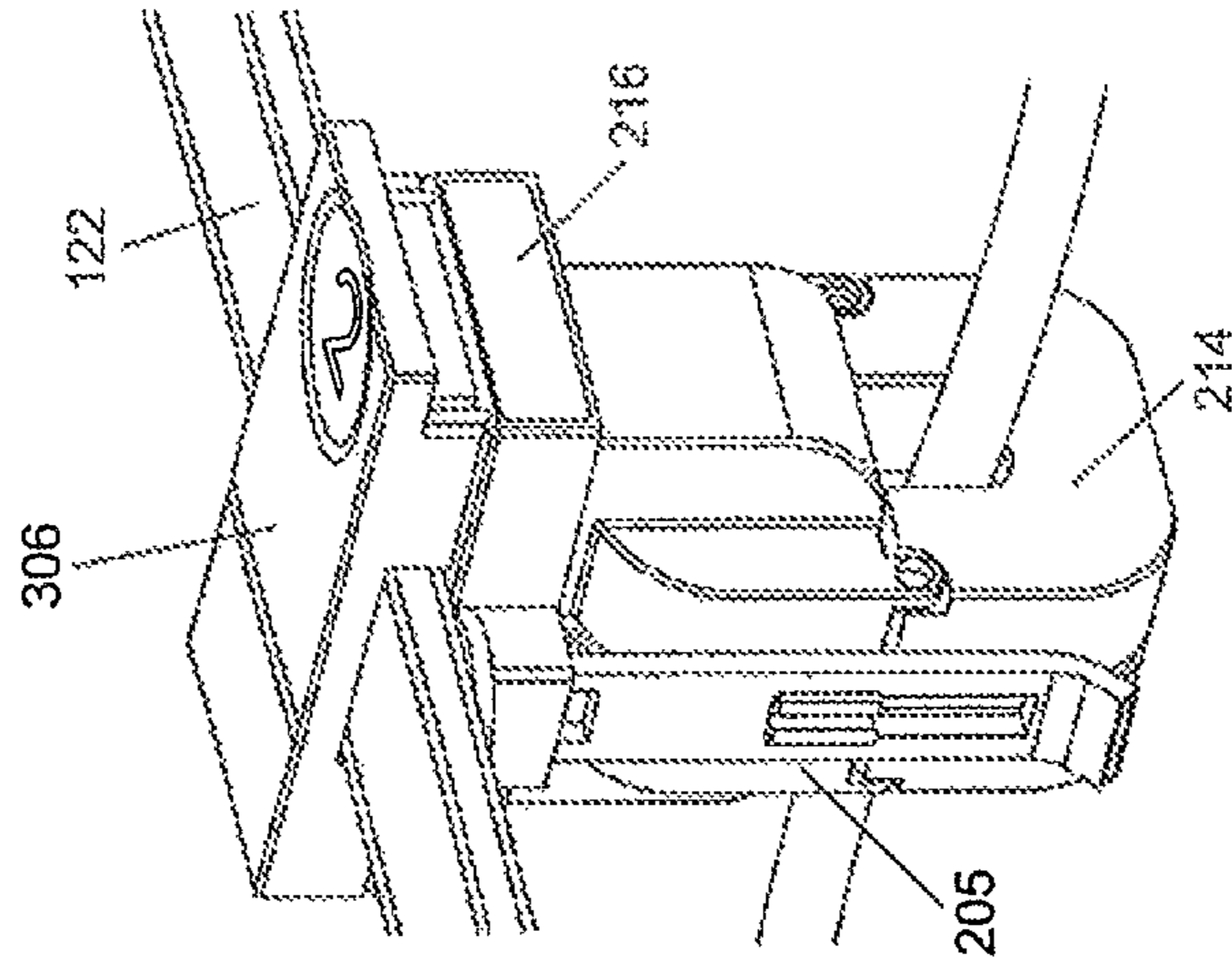


FIG. 3C

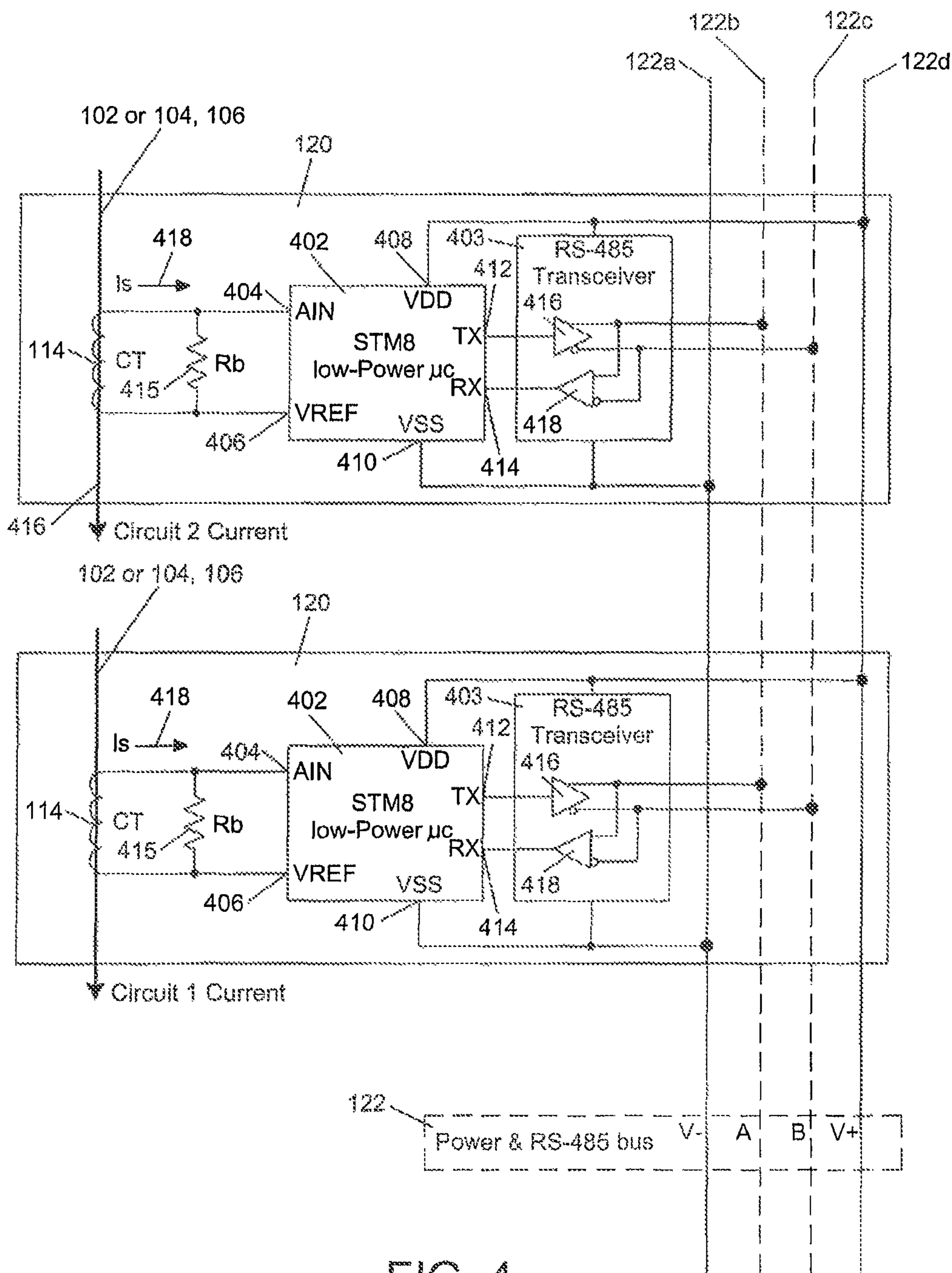


FIG. 4





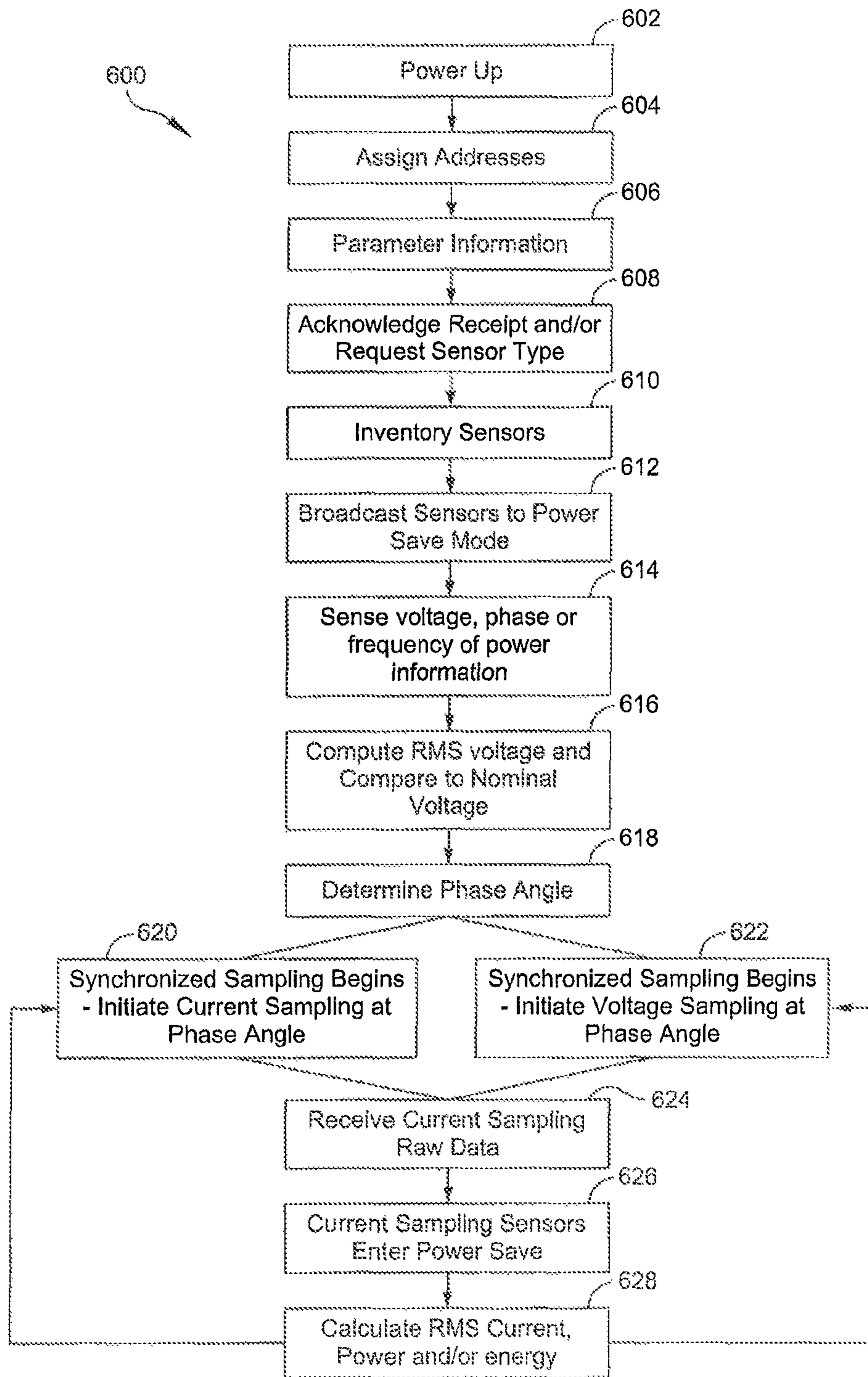


FIG. 6

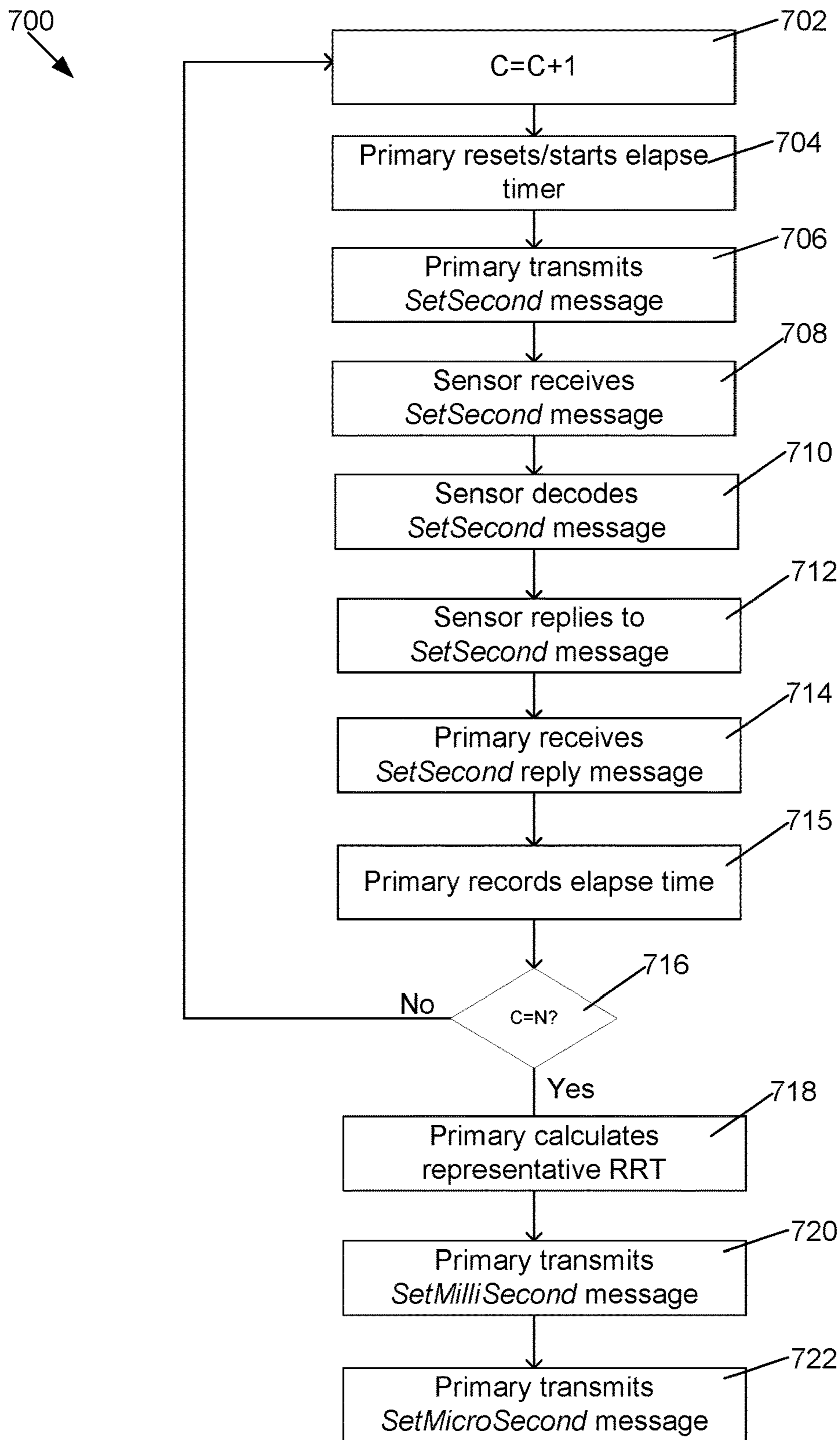


FIG. 7



## AUTOMATIC SUB-MILLISECOND CLOCK SYNCHRONIZATION

### CROSS-REFERNCE TO REALTED APPLICATIONS

This application is a U.S. National Stage Application under 35 U.S.C. § 371 of International Application No. PCT/US2013/078448, filed Dec. 31, 2013, titled AUTOMATIC SUB-MILLISECOND CLOCK SYNCHRONIZATION, which is hereby incorporated herein by reference in its entirety.

### BACKGROUND OF INVENTION

#### Field of the Invention

At least one example in accordance with the present invention relates generally to systems and methods for monitoring a load center for current, power and energy usage.

#### Discussion of Related Art

A load center or panelboard is a component of an electrical supply system which divides an electrical power feed from a power line into different subsidiary circuit branches. Each subsidiary circuit branch may be connected to a different load. Thus, by dividing the electrical power feed into subsidiary circuit branches, the load center may allow a user to individually control and monitor the current, power and energy usage of each load.

Current sensors can be used to monitor activity of a load center. For example, Current Transformers (CT) are commonly used to monitor current in a subsidiary or main branch of a load center while maintaining electrical isolation from the branch. A CT measures current in a branch by producing a reduced current signal, proportionate to the current in the branch. Based on the generated reduced current signal, the level of current in the subsidiary branch may be determined. The generated signal may also be further manipulated and measured to assist in efficient energy management.

### SUMMARY OF THE INVENTION

Aspects in accord with the present invention are directed to a system for monitoring a plurality of circuit branches coupled to an input line, the system comprising a communication bus, a controller having a primary clock with a first clock value, the controller configured to be coupled to the communication bus and the input line and further configured to sample voltage on the input line based on the first clock value, a plurality of sensor circuits, each sensor circuit having a secondary clock with a second clock value and each sensor circuit configured to be coupled to the communication bus and at least one of the plurality of circuit branches, wherein each sensor circuit is further configured to sample current in the at least one of the plurality of circuit branches based on the second clock value, and wherein the controller is further configured to initiate, via the communication bus, synchronization of at least one secondary clock and the primary clock, and to synchronize, via the communication bus, the at least one secondary clock and the primary clock to account for transmission latency in the communication bus.

According to one embodiment, the controller is further configured to utilize a multi-drop master-slave communication protocol to communicate with the plurality of sensor circuits via the communication bus. In another embodiment,

in initiating synchronization of the at least one secondary clock and the primary clock, the controller is further configured to transmit a measurement signal to at least one sensor circuit having the at least one secondary clock and to start a timer having an elapsed time value upon transmitting the measurement signal. In one embodiment, the at least one sensor circuit is further configured to receive the measurement signal and transmit a response to the measurement signal to the controller. In another embodiment, the at least one sensor circuit is further configured to adjust the second clock value of the secondary clock based on the measurement signal.

According to another embodiment, the controller is further configured to receive the response to the measurement signal from the at least one sensor circuit, stop the timer in response to receiving the response to the measurement signal, and calculate at least one Return Trip Time (RTT) based on the elapsed time value of the timer. In another embodiment, the controller is further configured to calculate a representative RTT based on the at least one RTT. In one embodiment, the representative RTT is one of a median RTT, mean RTT, and maximum RTT.

According to one embodiment, the controller is further configured to transmit a first synchronization signal based on the representative RTT to the at least one sensor circuit, and wherein the at least one sensor circuit is further configured to adjust the second clock value of the secondary clock based on the first synchronization signal. In one embodiment, the at least one sensor circuit is further configured to adjust a millisecond counter of the secondary clock based on the first synchronization signal. In another embodiment, the controller is further configured to transmit a second synchronization signal based on the representative RTT to the at least one sensor circuit, and wherein the at least one sensor circuit is further configured to adjust the second clock value based on the second synchronization signal. In one embodiment, the at least one sensor circuit is further configured to adjust a microsecond counter of the secondary clock based on the second synchronization signal.

According to another embodiment, the controller is further configured to synchronize, via the communication bus, current sampling performed by the plurality of sensor circuits with the voltage sampling performed by the controller.

Another aspect in accord with the present invention is directed to a method for monitoring a plurality of circuit branches coupled to a power line, the method comprising coupling a controller to the communication bus and to the power line, the controller having a primary clock with a first clock value, coupling a sensor circuit to each one of the plurality of circuit branches and to a communication bus, each sensor circuit having a secondary clock with a second clock value, sampling, with at least one of the sensor circuits, current in at least one of the plurality of circuit branches based on the second clock value, sampling, with the controller, voltage on the power line based on the first clock value, and synchronizing, with the controller via the communication bus, the at least one secondary clock and the primary clock to account for transmission latency in the communication bus.

According to one embodiment, synchronizing the at least one secondary clock and the primary clock includes calculating at least one RTT from the controller to at least one sensor circuit having the at least one secondary clock, and transmitting at least one synchronization signal from the controller to the at least one sensor circuit to adjust the second clock value of the secondary clock of the at least one sensor circuit based on the at least one RTT.



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According to another embodiment, calculating at least one RTT includes transmitting a measurement signal from the controller to the at least one sensor circuit, in response to transmitting the measurement signal, starting a timer of the controller having an elapsed time value, receiving, with the at least one sensor circuit, the measurement signal, transmitting, in response to receiving the measurement signal, a response to the measurement signal from the at least one sensor circuit to the controller, receiving, with the controller, the response to the measurement signal, stopping, in response to receiving the response to the measurement signal, the timer of the controller, and calculating the at least one RTT based on the elapsed time value of the timer. In one embodiment, the method further comprises calculating a representative RTT based on a plurality of RTT calculations, and wherein transmitting at least one synchronization signal from the controller to the at least one sensor circuit includes transmitting at least one synchronization signal from the controller to the at least one sensor circuit to adjust the second clock value of the at least one sensor circuit based on the representative RTT.

According to one embodiment, the method further comprises synchronizing, with the controller via the communication bus, current sampling performed by the plurality of sensor circuits with the voltage sampling performed by the controller. In one embodiment, transmitting at least one synchronization signal from the controller to the at least one sensor circuit to adjust the second clock value of the at least one sensor circuit based on the at least one RTT includes utilizing a multi-drop master-slave communication protocol to transmit the at least one synchronization signal from the controller to the at least one sensor circuit.

One aspect in accord with the present invention is directed to a system for monitoring a plurality of circuit branches coupled to an input line, the system comprising a communication bus, a controller having a primary clock having a first clock value, the controller configured to be coupled to the communication bus and the input line and further configured to sample voltage on the input line based on the first clock value, a plurality of sensor circuits, each sensor circuit having a secondary clock with a second clock value and each sensor circuit configured to be coupled to the communication bus and at least one of the plurality of circuit branches, wherein each sensor circuit is further configured to sample current in the at least one of the plurality of circuit branches based on the second clock value, and means for synchronizing, with the controller via the communication bus, the secondary clock of at least one of the plurality of sensor circuits and the primary clock of the controller to within 0.1 millisecond.

## BRIEF DESCRIPTION OF DRAWINGS

The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various FIGs. is represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing. In the drawings:

FIG. 1 is a circuit diagram of a load center in accordance with aspects of the present invention;

FIG. 2A is a schematic diagram of a smart CT prior to being coupled to a circuit branch in accordance with aspects of the present invention;

FIG. 2B is a schematic diagram of a smart CT after being coupled to a circuit branch in accordance with aspects of the present invention;

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FIG. 3A is a schematic diagram of a smart CT prior to being coupled to a communication bus in accordance with aspects of the present invention;

FIG. 3B is a schematic diagram of a smart CT after being coupled to a communication bus in accordance with aspects of the present invention;

FIG. 3C is a schematic diagram of a smart CT locked together with a communication bus in accordance with aspects of the present invention;

FIG. 4 is a circuit diagram of smart CT's coupled to a daisy chain bus in accordance with aspects of the present invention;

FIG. 5 is a block diagram of a concentrator in accordance with aspects of the present invention;

FIG. 6 is a flow chart of a method of operation of a CT concentrator in accordance with aspects of the present invention; and

FIG. 7 is a flow chart illustrating a method of clock synchronization between a CT concentrator and smart CT's in accordance with aspects of the present invention.

## DETAILED DESCRIPTION

Examples of the methods and systems discussed herein are not limited in application to the details of construction and the arrangement of components set forth in the following description or illustrated in the accompanying drawings. The methods and systems are capable of implementation in other embodiments and of being practiced or of being carried out in various ways. Examples of specific implementations are provided herein for illustrative purposes only and are not intended to be limiting. In particular, acts, components, elements and features discussed in connection with any one or more examples are not intended to be excluded from a similar role in any other examples.

Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. Any references to examples, embodiments, components, elements or acts of the systems and methods herein referred to in the singular may also embrace embodiments including a plurality, and any references in plural to any embodiment, component, element or act herein may also embrace embodiments including only a singularity. References in the singular or plural form are not intended to limit the presently disclosed systems or methods, their components, acts, or elements. The use herein of "including," "comprising," "having," "containing," "involving," and variations thereof is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. References to "or" may be construed as inclusive so that any terms described using "or" may indicate any of a single, more than one, and all of the described terms. In addition, in the event of inconsistent usages of terms between this document and documents incorporated herein by reference, the term usage in the incorporated references is supplementary to that of this document; for irreconcilable inconsistencies, the term usage in this document controls.

As discussed above, CT's may be utilized with a load center of an electrical supply system to monitor circuit branches and assist in providing efficient energy management. For instance, CT's may be coupled to circuit branches inside or outside of a load center. However, multiple challenges with CT's may arise as the electrical supply system grows in size and complexity.

Existing methods and systems typically rely on a system of individual CT's, each connected to a main controller and measurement unit in a "hub and spoke" topology. In such a



system, each CT requires dedicated cabling connecting it to the main controller and its measurement unit, so that the number of cables or wires increases linearly with the number of sensors. In addition, some jurisdictions have regulatory requirements on the amount of “gutter space” (i.e., space within the panelboard free of wiring and other electronic devices) available within a panelboard. Therefore, as the number of CT’s increases, the amount of cabling and circuitry within a panelboard may become difficult to manage and violate regulatory requirements.

In some instances it may even be difficult to physically place all of the desired CT’s and corresponding circuitry within the load center, and due to the complexity of such a load center; installation, expansion and maintenance may also be expensive, difficult and even hazardous.

At least some embodiments described herein overcome these problems and provide a relatively small, less complex and more manageable method and system for utilizing CT’s to monitor circuit branches of a load center.

FIG. 1 shows a load center 100 that includes a system for monitoring subsidiary circuit branches 102 of the load center 100 according to one embodiment of the current invention. The load center 100 includes a housing 101. Within the housing 101, the load center 100 includes a first input power line 104, a second input power line 106, a plurality of circuit branches 102, a neutral line 108, and a ground connection 110. The first and second input power lines 104, 106 are each configured to be coupled to an external power source (e.g., a utility power system) (not shown). Each one of the plurality of circuit branches 102 is configured to be coupled between one of the input power lines 104, 106 and an external load 112 (e.g., an appliance, a power outlet, a light etc.). According to one embodiment, each one of the input power lines 104, 106 includes a circuit breaker 113 coupled between the input power line 104, 106 and circuit branches 102. According to another embodiment, each one of the plurality of circuit branches 102 includes a circuit breaker 115 coupled between the input power line 104, 106 and an external load 112. In one embodiment, the current rating of each of the circuit breakers 113, 115 may be configured based on the power required by the external load 112 to which the circuit breakers 113, 115 associated circuit branch 102 is coupled. The neutral line 108 is coupled to the ground connection 110. According to one embodiment, the neutral line is coupled to the ground connection 110 via a neutral bus bar 116. According to another embodiment, the ground connection 110 is coupled to the neutral line 108 via a ground bus bar 118.

Within the housing 101, the load center 100 also includes a plurality of Current Transformers (CT) 114, a plurality of smart sensor circuits 120, a communication bus 122, and a CT concentrator 124. According to one embodiment, the communication bus 122 includes a plurality of wires. For example, in one embodiment, the communication bus 122 is a ribbon cable including 4 wires (a power line, a return line, D+ differential pair line, D- differential pair line); however, in other embodiments, the communication bus 122 may include any number and type of wires. Each one of the plurality of CT’s 114 is coupled to at least one of the plurality of circuit branches 102. According to one embodiment, CT’s 114 may also be coupled to each input line 104, 106. According to one embodiment, each CT 114 encompasses a corresponding circuit branch 102 or input line 104, 106. Each one of the plurality of CT’s is also coupled to a corresponding smart sensor circuit 120. Each smart sensor circuit 120 is coupled to the communication bus 122.

According to one embodiment, each smart sensor circuit 120 is connected to the communication bus 122 so that each smart sensor circuit 120 is in electrical communication with the CT concentrator 124. In one embodiment, each smart sensor circuit 120 is clamped onto the communication bus 122. For example, in one embodiment, electrical contacts (not shown) of a smart sensor circuit 120 are pressed onto the communication bus 122 so that the electrical contacts pierce an insulation layer of the communication bus 122 and become electrically coupled to appropriate conductors within the communication bus 122. In other embodiments, the smart sensor circuits 120 may be coupled differently to the communication bus 122. For example, according to one embodiment, the smart sensor circuits 120 may be coupled to the communication bus 122 via a bus bar or daisy chained connectors (not shown).

The connection of smart sensor circuits 120 to the communication bus 122 is discussed in greater detail below.

According to one embodiment, the CT concentrator 124 includes a digital interface 125, at least one analog interface 127, a power module 126 and a Zigbee RF interface 128. The communication bus 122 is coupled to the digital interface 125. The power module 126 is coupled to at least one input power line 104, 106 via at least one branch circuit 102.

According to one embodiment (not shown), at least one CT 114 is coupled directly to at least one analog interface 127. According to one embodiment, AC power is provided from an external source (e.g., a utility power system) to the input lines 104, 106. AC power from the input lines 104, 106 is provided to each of the external loads 112, via the circuit branches 102. The circuit breakers 113 are configured to automatically open and prevent current in an input line 104, 106 if an overload or short circuit is detected in the input line 104, 106. The circuit breakers 115 are configured to automatically open and prevent current in a circuit branch 102 if an overload or short circuit is detected in the circuit branch 102.

The power module 126 of the CT concentrator 124 receives AC power from at least one input line 104, 106. Using the AC power, the power module 126 powers the CT concentrator 124. In addition, the CT concentrator 124 measures the AC voltage, frequency and/or phase of the AC power. According to one embodiment, the CT concentrator 124 is configured to communicate the measured AC voltage, frequency and/or phase information to the smart sensor circuits 120, via the communication bus 122. For example, in one embodiment, the CT concentrator 124 transmits phase information of the AC power and/or timing/clock information to the smart sensor circuits 120 so that the CT concentrator 124 may be synchronized with the smart sensor circuits 120. The synchronization of the CT concentrator 124 with the smart sensor circuits 120 will be discussed in greater detail below. According to one embodiment, the CT concentrator is also capable of being powered by a battery.

AC current passing through a circuit branch 102 or input line 104, 106 induces a proportionate AC current in its associated CT 114 which encompasses the circuit branch 102 or input line 104, 106. According to one embodiment, where a CT 114 may be coupled to multiple circuit branches 102, an AC current proportionate to the combined current in the multiple circuit branches is induced in the CT 114 which encompasses the multiple circuit branches.

The smart sensor circuit 120 coupled to the CT 114 converts the proportionate AC current from the CT 114 into a digital value and then transmits the digital value, over the communications bus 122 to the CT concentrator 124. In addition, the smart sensor circuit 120 may be configured to



utilize the voltage, frequency and/or phase information received from the CT concentrator 124 over the communications bus 122. For example, in one embodiment, the smart sensor circuit 120 utilizes phase information and/or timing/clock information received from the CT concentrator 124 to synchronize operation with the CT concentrator 124 such that current measurements performed by the smart sensor circuits 120 can be synchronized with voltage measurements made by the CT concentrator 124.

In another example, the smart sensor circuit 120 utilizes the voltage, frequency and/or phase information to calculate power and energy information such as RMS current, true and apparent power, and power factor of the circuit branch 102 or input line 104, 106. This information is also converted into digital values and sent to the digital interface 125 of the CT concentrator 124 over the communications bus 122. According to one embodiment, at least one CT 114 may also provide analog signals, proportionate to the AC current passing through the circuit branch 102, directly to an analog interface 127 of the CT concentrator 124.

According to one embodiment, upon receiving the current information from the smart sensor circuits 120, the CT concentrator 124 utilizes the measured voltage, frequency and/or phase information to calculate power and energy information such as RMS current, true and apparent power, and power factor of the circuit branch 102 or input line 104, 106.

According to one embodiment, upon receiving the current information and receiving and/or calculating the power information, the CT concentrator 124 transmits the current, power and energy information to an external client (e.g., a web server, in-home display, internet gateway etc.) via the wireless Zigbee RF interface 128 to assist in power management of the load center 100 and to assist in power management and control of a residence or other facility containing the system. The CT concentrator 124 may also transmit the current, power and energy information to an external client via a wired connection or a different type of wireless connection.

By including a single communication bus 122 to which all smart sensor circuits 120 are coupled, a relatively small, less complex and more manageable method and system for utilizing a plurality of CT's 114 to monitor circuit branches 102 of a load center 100 is provided.

FIGS. 2A and 2B illustrate one embodiment of the process of coupling a CT 114 to a circuit branch 102. According to one embodiment, a housing 205 includes a CT 114 and a smart sensor circuit 120 enclosed therein. In one embodiment, a first portion 214 of the housing 205 includes a CT 114 and a second portion 216 includes a smart sensor circuit 120. FIG. 2A illustrates the first portion 214 prior to being coupled to a circuit branch 102 and FIG. 2B illustrates the first portion 214 after being coupled to a circuit branch 102.

The first portion 214 is coupled to the second portion 216 via a hinge 206. The second portion 216 includes a button 202 coupled to a lever 204. Prior to the first portion 214 being coupled to the circuit branch 102, the lever 114 is in an upward position, allowing the first portion 214 to swing away from the second portion 216 and create an opening 208 by which a circuit branch 102 may be inserted. When connection to a circuit branch 102 is desired, a user may configure the first portion 214 so that the circuit branch 102 is inserted through the opening 208 into an interior chamber 209. The user may then press down on the button 202, causing the lever 204 to move in a downwards direction. The lever 204 presses against an outside portion 210 of the first portion 214, causing the first portion 214 to swing towards

the second portion 216 and capture the circuit branch 102 within the interior chamber 209 of the first portion 214. According to other embodiments, the first portion 214 may be connected to the circuit branch 102 differently. For example, the first portion 214 may be manually placed around the circuit branch 102. As discussed above, after the circuit branch 102 is encompassed by the first portion 214 (and hence also the CT 114), an AC current in the circuit branch 102 will produce a proportionate AC current within the CT 114.

FIGS. 3A, 3B and 3C illustrate the process of coupling the second portion 216 to a communications bus 122. FIG. 3A illustrates the second portion 216 prior to being connected to a communications bus 122. FIG. 3B illustrates the second portion 216 after being connected to a communication bus 122. FIG. 3C illustrates the second portion 216 locked together with a communications bus 122. According to one embodiment, the second portion 216 includes an Insulation Displacement Connector (IDC) 302 (e.g., an AVX series 9176 IDC). According to one embodiment, the IDC 302 may include a plurality of blades 304. For example, if, as discussed above, the second portion 216 (and hence the smart sensor circuit 120) is configured to be coupled to a four-wire ribbon cable, the IDC 302 will include four blades, each blade configured to be coupled to a corresponding conductor within the cable. However, according to other embodiments, the IDC 302 may include any number of blades to adequately connect the smart sensor circuit 120 to the communications bus 122.

The second portion 216 may also include a locking lid 306 coupled to the second portion 216 via a hinge 308. Prior to being coupled to the communications bus 122, the locking lid 306 of the second portion 216 is swung away from the IDC 302, allowing a user to place the communication bus 122 adjacent to the IDC 302. The user presses down on the communication bus 122, causing the communication bus 122 to press against the IDC 302. The plurality of blades 304 of the IDC 302 pierce the outer insulation layer 310 of the communication bus 122, each one of the plurality of blades 304 connecting with a corresponding conductor within the communication bus 122. The user may then swing the locking lid towards the IDC 302 and press down on the locking lid to lock the communication bus 122 into place. According to other embodiments, the second portion 216 (and hence the smart sensor circuits 120) may be coupled to the communication bus 122 in a different manner. For example, smart sensor circuits may also be coupled to the communication bus 122 via a bus bar. Upon being coupled to the communication bus 122, the smart sensor circuit 120 is in electrical communication with the CT concentrator 124.

FIG. 4 is a circuit diagram of a plurality of CT's 114 and smart sensor circuits 120 coupled to a communication bus 122. Each CT 114 is coupled to a circuit branch 102, or input line 104, 106, as discussed above. For example, in one embodiment each CT 114 is configured to encompass a circuit branch 102, or input line 104, 106, as discussed in relation to FIGS. 2A and 2B. Each smart sensor circuit 120 is coupled to a communication bus 122 as discussed above. According to one embodiment, the communication bus 122 may be a 4-wire ribbon cable including a power line 122d, a D- differential pair line 122c, a D+ differential pair line 122b, and a return (ground) line 122a. In one embodiment, the communication bus 122 is a RS-485 bus; however, according to other embodiments, a different type of bus may be used.

Each smart sensor circuit 120 includes a microcontroller 402. In one embodiment, the microcontroller 402 is a low



power microcontroller (e.g., an STM8 low power microcontroller). According to one embodiment, the microcontroller **402** includes an analog interface **404**, a reference interface **406**, a power interface **408**, a return interface **410**, a transmission interface **412** and a reception interface **414**. According to one embodiment, the power interface **408** is coupled to the power line **122d** and the return interface **410** is coupled to the return line **122a**. In this way, each smart sensor circuit **120** is powered by the communication bus **122**. According to another embodiment, each CT **114** is coupled in parallel between the analog interface **404** and the reference interface **406**. In one embodiment, each smart sensor circuit **120** also includes a burden resistor **415** coupled in parallel between the analog interface **404** and the reference interface **406**.

Each smart sensor circuit **120** also includes a transceiver **403** (e.g., an RS-485 Transceiver). According to one embodiment, the transceiver **403** includes a first diode **416** coupled between the transmission interface **412** and the communication bus **122**, and a second diode **418** coupled between the reception interface **414** and the communication bus **122**. Also, in one embodiment, the transceiver **403** is coupled in parallel between the power **122d** and return **122a** lines.

As discussed previously, AC current **416** in the circuit branch **102** or input line **104**, **106** to which a CT **114** is coupled, will produce a proportionate AC current **418** in the CT **114**. The burden resistor **415** converts the proportionate AC current **418** into a proportionate AC voltage. Via the analog interface **404**, the microcontroller **402** receives the proportionate AC voltage and converts the proportionate AC voltage into a digital value. The microcontroller **402** then provides the digital value to the transmission line **122b** via the transmission interface **412** and transceiver **403**, and transmits the digital value over the communication bus **122** to the CT concentrator **124**. In addition, the microcontroller **402** is configured to receive voltage, frequency and/or phase information from the CT concentrator **124**, via the reception line **122c**, the transceiver **403** and the reception interface **414**. As discussed above, the microcontroller **402** may use the additional voltage, frequency and/or phase information received from the CT concentrator **124** along with the received proportionate AC current **418** to calculate power and energy information of the circuit branch **102** or input line **104**, **106** such as RMS current, true and apparent power, and power factor. This information may also be converted into digital values and transmitted to the CT concentrator **124** via the transmission interface **412**, the transceiver **403** and the transmission line **122b**. In one embodiment, the microcontroller **402** may also use phase information and/or timing/clock information received from the CT concentrator **124** to synchronize current measurements in the smart sensor circuits **120** with voltage measurements in the CT concentrator **124**.

FIG. **5** is a block diagram of a CT concentrator **124**. As discussed above, the CT concentrator **124** has a digital interface **125** coupled to the communication bus **122**. The communications bus is coupled to a plurality of smart sensor circuits **120** and a plurality of CT's **114**.

According to one embodiment, the CT concentrator **124** includes a power module **126**. In one embodiment, the power module **126** includes a single-phase power interface **502** configured to be coupled to a single-phase power supply. In another embodiment the power module **126** includes a three-phase power interface **504** configured to be coupled to a three-phase power supply. For example, the three-phase power interface **504** may be configured to

receive power from a 3-phase delta or wye power connection. It is to be appreciated that the power supply coupled to the single-phase **502** or three-phase **504** interface is the same power supply coupled to the input lines **104**, **106** and as described in relation to FIG. **1**. Accordingly, power received by the power module **126** is substantially the same as power being provided to the circuit branches **102**.

According to one embodiment, the power module **126** also includes a DC interface **506**, a sensor interface **508** and an extra pin interface **510**. According to one embodiment, the extra pin interface **510** includes four additional pins (e.g., a transmission pin, a reception pin, a power module type pin and an auxiliary power pin). However, in other embodiments, the extra pin interface **510** may include any number and type of pins. According to another embodiment, the CT concentrator **124** may also include a battery pack **512** having a DC interface **514**. In one embodiment, the power module **126** and/or battery pack **512** is modular and may be removed from the CT concentrator **124**.

According to one embodiment, the CT concentrator **124** includes a first DC interface **516** configured to be coupled to the DC interface **514** of the battery pack **512**, a second DC interface **518** configured to be coupled to the DC interface **506** of the power module **126**, a sensor interface **520** configured to be coupled to the sensor interface **508** of the power module **126**, and an extra pin interface **522** configured to be coupled to the extra pin interface **510** of the power module **126**. The extra pin interface **522** includes four additional pins (e.g., a transmission pin, a reception pin, a power module type pin and an auxiliary power pin). However, in other embodiments, the extra pin interface **522** may include any number and type of pins.

The first **516** and second **518** DC interfaces are coupled to a power management module **524**. The power management module **524** is coupled to a microcontroller **528**. The sensor interface **520** and the extra pin interface **522** are coupled to the microcontroller **528**. The CT concentrator **124** also includes a transceiver **530** coupled between the digital interface **125** and the microcontroller **528** and a non-volatile memory module **532** coupled to the microcontroller **528**. In one embodiment, the non-volatile memory module **532** includes Electrically Erasable Programmable Read-Only Memory (EEPROM); however, in other embodiments, the non-volatile memory module **532** may include any type of non-volatile memory (e.g., such as serial Flash memory).

The CT concentrator **124** also includes a user interface **534** coupled to the microcontroller. In some embodiments, the user interface may include any type of controls which allows a user to interface with the CT concentrator **124**. (e.g., such controls include switches, buttons, LED's etc.). According to one embodiment, the CT concentrator **124** also includes a USB port **536** and a serial port **538**.

The CT concentrator **124** also includes a wireless radio module and antenna **540**. In one embodiment, the wireless radio module is a ZigBee radio; however, in other embodiments, the wireless radio module **540** may be configured using a different wireless standard. According to one embodiment, the wireless radio and antenna **540** is coupled to the microcontroller **528**, an On/Off switch **542**, and a serial memory module **544**.

The power module **126** receives AC power from a power source (e.g., a single-phase or three phase power source) (not shown), modulates and converts the received AC power to DC power, and provides DC power to the CT concentrator **124** via the DC interface **506** and the second DC interface **518**. The power management module **524** receives the DC power from the second DC interface **518** and provides



appropriate DC power to components of the CT concentrator **124** (e.g., the microcontroller **528**). According to another embodiment, the battery pack **512** may provide DC power to the CT concentrator **124** via the DC interface **514** and the first DC interface **516**. The power management module **524** receives the DC power from the first DC interface **516** and provides appropriate DC power to components of the CT concentrator **124** (e.g., the microcontroller **528**).

The power module **126** provides power signals received from the power source (e.g., single-phase or three-phase source) to the microcontroller **528** via the sensor interfaces **508**, **520**. In one embodiment, the power signals include a voltage sense signal and a phase synchronization signal. According to another embodiment, the power module **126** also provides additional information to the microcontroller via the extra pin interfaces **510**, **522**. For example, additional information may be provided to the microcontroller via a transmission pin, a reception pin, a power module type pin and an auxiliary power pin.

The microcontroller **528** receives the power signal information from the power module **126**, via the sensor interface **520**. The microcontroller **528** measures the voltage, frequency and phase of the power being provided to the power module **126**. It is to be appreciated that as the power provided to the power module **126** is substantially the same as power provided to the circuit branches **102** (as discussed above), the voltage, frequency and phase measured by the microcontroller **528** in relation to the power module **126** is the same as the voltage, frequency and phase of the power being provided to the circuit branches **102**.

Upon being powered, the microcontroller **528** begins to communicate with the smart sensor circuits **120** via the transceiver **530**, the digital interface **125** and the communication bus **122**. According to one embodiment, the microcontroller **528** may utilize the RS-485 physical communication protocol to communicate over the communication bus **122**. However, other physical communication protocols may be used. The microcontroller **528**, which acts as the primary controller, identifies which smart sensor circuits **120** are coupled to the communication bus **122**. The primary microcontroller **528** treats the microcontrollers **402** as secondary controllers and assigns each secondary microcontroller **402** (and hence smart sensor circuit **120**) a unique address. According to one embodiment, each time a new smart sensor circuit **120** is coupled to the communication bus **122**, it is assigned a new address by the primary microcontroller **528**.

According to one embodiment, the primary microcontroller **528** utilizes the Modbus serial communication protocol to define the communication and addressing on the communication bus **122**. The primary microcontroller **528**, using the Modbus protocol, assigns unique addresses to the smart sensor circuits **120** and sets the structure and format of the data that is transmitted over the communication bus **122**. For example, according to one embodiment, communication over the communication bus **122** using the Modbus protocol may be performed as described in U.S. patent application Ser. No. 13/089,686 entitled "SYSTEM AND METHOD FOR TRANSFERRING DATA IN A MULTI-DROP NETWORK", filed on Apr. 19, 2011, which is herein incorporated by reference in its entirety. In one embodiment, the primary microcontroller **528** utilizes an auto addressing scheme. For example, the primary microcontroller **528** utilizes an auto addressing scheme as described in U.S. patent application Ser. No. 13/089,678 entitled "SYSTEM AND METHOD FOR AUTOMATICALLY ADDRESSING

DEVICES IN A MULTI-DROP NETWORK", filed on Apr. 19, 2011, which is herein incorporated by reference in its entirety.

According to one embodiment, the Modbus protocol allows for up to **255** smart sensor circuits **120** to be simultaneously attached to the communication bus **122**. It also is to be appreciated that the number of smart sensor circuits **120** may be limited by the load center **100** itself. For example, in common residential load centers, the maximum number of branch circuits (and hence smart sensor circuits) is seventy-two. However, according to at least one embodiment, different communication protocols may be used by the primary **528** and secondary **402** microcontrollers to allow any number of smart sensor circuits **120** to be coupled to the communication bus **122** (e.g., for use in large, commercial load centers).

According to one embodiment, once all of the smart sensor circuits **120** have been identified and assigned addresses by the primary microcontroller **528**, a user, via the user interface **534**, may associate each smart sensor circuit **120** with a specific load (e.g., sensor #**12** is assigned to an air conditioner; sensor #**13** is assigned to a Refrigerator, etc.).

Once the identification and addressing of the smart sensor circuits **120** is complete, the primary microcontroller **528** controls the smart sensor circuits **120**. The primary microcontroller **528** controls communication on the bus **122** to eliminate conflicts or data collision. In addition, according to one embodiment, the primary microcontroller **528** provides power related information or data to the smart sensor circuits **120**. For example, as discussed above, the primary microcontroller **528** measures the voltage, frequency and phase of the power being provided to the power module **126** (and hence the circuit branches **102**). When needed by a smart sensor circuit **120**, the primary microcontroller **528** transmits the power related information (and/or other appropriate information such as timing/clock information) to the smart sensor circuit **120**, via the transceiver **530** and communication bus **122**.

As discussed above, each smart sensor circuit **120** measures the current through an associated circuit branch **102** or input line **104**, **106**. According to one embodiment, using the measured current and the received additional power related information (e.g., voltage, frequency and phase) from the primary microcontroller **528**, a smart sensor circuit **120** calculates power information such as RMS current, true and apparent power, and power factor of the associated circuit branch **102** or input line **104**, **106**. The calculated current and/or power information is transmitted to the primary microcontroller **528**, via the communication bus **122**, digital interface **125**, and transceiver **530**. In one embodiment, the power information is transmitted to the primary microcontroller **528** at a time and rate determined by the microcontroller **528**.

According to one embodiment, upon receiving the calculated current from the smart sensor circuits **120**, the primary microcontroller **528** utilizes the measured voltage, frequency and/or phase information to calculate power and energy information such as RMS current, true and apparent power, and power factor of the circuit branch **102** or input line **104**, **106**.

The current, power and energy information is provided to the wireless radio module and by the primary microcontroller **528**. The wireless radio module wirelessly transmits (via the antenna **540**) the current, power and energy information to an external client (e.g., a web server, in-home display, or internet gateway) to provide electric power and



energy consumption data to end users or other interested parties. According to one embodiment, the current, power and energy information may also be provided to an external client through a wired connection (e.g., via the USB port **536** or serial port **538**). According to another embodiment, the current, power and energy information may be provided to an external client through another wired type of interface, such as an Ethernet or Power Line Communication (PLC) port.

In one embodiment described above, each smart sensor circuit **120** determines power information for its associated branch circuit and transmits the information to the CT concentrator **124**. In another embodiment, which will now be described with reference to FIG. **6**, the CT concentrator **124** synchronizes current measurements by each smart sensor circuit **120** with voltage measurements performed by the CT concentrator **124**. This allows the CT concentrator **124** to calculate power information based only on current information received from the smart sensor circuits **120**.

FIG. **6** is a flow chart of a method of operation of the CT concentrator **124** of FIG. **5**, according to one embodiment. At block **602**, the CT concentrator **124**, and hence the smart sensor circuits **120**, are powered up. At block **604**, the primary microcontroller **528** of the CT concentrator assigns unique addresses to each smart sensor circuit **120**, via the communications bus **122**. According to one embodiment, the primary microcontroller **528** utilizes an auto addressing scheme, as discussed above. At block **606**, the primary microcontroller **528** transmits control information to each smart sensor circuit **120**, via the communication bus **122**. According to one embodiment, the control information includes at least one of frequency (or period), the number of samples per period, and a defined sleep timer. In another embodiment, the control information includes scaling parameters. According to another embodiment, the control information includes previous cycle computation results (e.g., for RMS current, power, energy).

At block **608**, the primary microcontroller **528** requests each smart sensor circuit **120** to acknowledge the receipt of the control information via the communication bus **122**. According to one embodiment, at block **608**, the primary microcontroller **528** also requests that each smart sensor circuit **120** transmit its sensor type (e.g., 20 A, 80 A, or 200 A current transformer) to the primary microcontroller **528** via the communication bus **122**. At block **610**, the primary microcontroller **528** creates an inventory of all of the sensor circuits **120** and their type (e.g., by model number). At block **612**, the primary microcontroller **528** transmits to each smart sensor circuit **120** that the smart sensor circuit **120** should enter power save mode.

According to one embodiment, once a smart sensor **120** enters power save mode, a sleep timer is enabled. In one embodiment, the use of the sleep timer is intended to limit the overall power consumption of the system. For example, in one embodiment, when a smart sensor **120** is in power save mode, the smart sensor **120** will not communicate on the communication bus, and hence will require a lower level of power, until the sleep timer has expired. By placing at least a portion of the smart sensors **120** in power save mode, the total number of smart sensors **120** requiring full power is limited and the total peak power consumption of the system may be reduced. According to one embodiment, the sleep timer is programmable. In one embodiment, the sleep timer is configured with a time equal to slightly less than the total number of smart sensors **120** multiplied by the period over which current is to be sampled.

For example, according to one embodiment, the sleep timer is configured with a time (T) calculated with the following formula:

$$T=(s-2)*t+(t/2);$$

where:

s represents the total number of smart sensors **120**, and t represents the sample period defined by the primary microcontroller **528**.

In one example, where the sample period is 20 ms and the system includes a total of 6 smart sensors **120**, the time T is calculated as 90 ms. In this example, after a smart sensor **120** has conducted measurements and finished transmitting current sample raw data, it will enter power save mode for 90 ms and will not sample current again until time T (90 ms) has expired. However, in other embodiments, the sleep timer may be configured differently.

In one embodiment, smart sensors **120** currently in power save mode are configured to exit power save mode early (i.e., before the expiration of time T), to prepare for current sampling which will begin upon the expiration of time T. For example, in one embodiment, smart sensors **120** currently in power save mode are configured to exit power save mode 10 ms early. In such an embodiment, the total time each smart sensor **120** will be awake is 30 ms (20 ms period in addition to 10 ms awakening period). Hence, by staggering the current sampling performed by the smart sensors **120**, the number of smart sensors **120** requiring power at the same time is limited and as a result, the total peak power consumption of the system is reduced. This is particularly useful for battery operated systems.

According to another embodiment, rather than utilizing a sleep timer, a smart sensor **120** exits power save mode upon detecting traffic on the communication bus **122**.

At block **614**, the primary microcontroller **528** senses the voltage, frequency and/or phase of the power signal information received from the power module **126** via the sensor interface **520**. For example, according to one embodiment, the primary microcontroller **528** senses voltage and/or frequency through a voltage sense signal and the primary microcontroller **528** senses phase through a phase synchronization signal. As discussed above, according to some embodiments, the power signal information received from the power module **126** may be correlated to single, double or 3-phase power.

At block **616**, the primary microcontroller **528** computes the RMS voltage for all phases that are present (e.g., 1, 2, or 3). Also at block **616**, the primary microcontroller **528** compares the RMS voltage to the primary microcontroller's **528** nominal voltage to confirm that the RMS voltage and phase signal(s) are correct. For example, according to one embodiment, if the primary microcontroller **528** is connected to a utility system in North America, the primary microcontroller **528** will confirm that it is measuring a 120V, 60 Hz signal. However, in another embodiment, if the primary microcontroller **528** is connected to a utility system in Europe, the primary microcontroller **528** will confirm that it is measuring a 220V, 50 Hz signal.

At block **618**, the primary microcontroller **528** determines the appropriate phase angle at which synchronized measurements will be taken. According to one embodiment, the phase angle may be configured as any phase angle, and does not have to be limited to a zero crossing. In some embodiments, the phase angle may be configured at an angle other than at a zero crossing to intentionally avoid noise which may exist at the zero crossing.



At blocks 620 and 622, synchronized sampling by the primary microcontroller 529 and the smart sensor circuits 120 begins at the previously determined phase angle. For example, according to one embodiment, at block 620, the primary microcontroller 528 communicates to all of the smart sensor circuits 120 simultaneously via the communication bus 122 to start sampling current in their respective circuit branches 102 at the predetermined phase angle. Also, at the same time as block 620, the primary microcontroller 528 at block 622 initiates voltage sampling of the power signal information received from the power module 126 at the previously determined phase angle to synchronize the voltage measurements with the current measurements made by all of the smart sensor circuits 120. According to one embodiment, the primary microcontroller 528 samples voltage over the same period of time in which the smart sensor circuits 120 sample current.

According to another embodiment, instead of communicating to all of the smart sensor circuits 120 simultaneously, the primary microcontroller 528 communicates to at least one specific sensor (e.g., a sensor having a unique address) to begin sampling current in the respective circuit branch 102. In this way, the primary microcontroller 528 is able to start sampling current in at least one specific type of circuit branch (e.g., a circuit branch coupled to a specific type of load). By only sampling current in a select number of circuit branches 102, the overall power consumption of the system may be reduced.

According to one embodiment, each smart sensor circuit 120 which is controlled to begin sampling will sample current in the smart sensor circuits 120 respective branch over a predefined period of time for a predefined number of samples, the time and number of samples being previously set by the primary microcontroller 528 in the control information. In one embodiment, the current sampling raw data is stored in a buffer of each smart sensor circuit 120.

At block 624, upon completing voltage sampling for the given period, the primary microcontroller 528 requests that each smart sensor circuit that was sampling current, transmit the current sampling raw data for the given time period from the buffer to the primary microcontroller 528 via the communication bus 122. According to one embodiment, the current sampling raw data is time-stamped.

At block 626, upon confirming receipt of the current sampling raw data, the primary microcontroller 528 transmits to the previous current sampling smart sensors 120 that the smart sensors 120 should enter power save mode, making more power available for other smart sensors (as discussed above).

According to one embodiment, at block 626, using the received current data and measured voltage data, the primary microcontroller 528 calculates the RMS current, real power (e.g., 4 quadrant), and/or energy usage of the circuit branches 102 associated with the smart sensors 102 from which the primary microcontroller 528 received the raw current sampling data. According to one embodiment, the primary microcontroller 528 may automatically account for any communication delay between the primary microcontroller 528 and the smart sensor circuits 120 when making its current, power and/or energy calculations. For example, in at least one embodiment, the primary microcontroller synchronizes the clock times of the smart sensor circuits 120 with the clock time of the primary microcontroller 528 to account for any communication delay between the primary microcontroller 528 and the smart sensor circuits 120 via the communication bus 122. Synchronization of the clock times between the primary microcontroller 528 and the smart

sensor circuits 120 to account for transmission latency by the communication bus 122 is discussed in greater detail below.

After calculating the current, power and energy information, the primary microcontroller 528 may repeat blocks 620 to 628 for another smart sensor 120 or group of smart sensors 120.

In at least some embodiments, the use of the primary microcontroller 528 to individually control the synchronization of the smart sensor circuits 120, eliminates any need to individually wire each smart sensor circuit 120 with phase synchronization signals from the power module. Phase Locked Loop (PLL) circuitry within the smart sensor circuits 120 may also be eliminated, as the primary microcontroller 528 will control the synchronization. By allowing the primary microcontroller 528 to select the phase angle at which sampling will occur, the flexibility of the system may be increased. For example, any appropriate phase angle may be selected to provide the most desirable results.

FIG. 7 is a flow chart 700 illustrating a method of clock synchronization between the primary microcontroller 528 of the CT concentrator 124 and smart sensor circuits 120 in accordance with aspects of the present invention. According to one embodiment, the clocks of the primary microcontroller 528 and the smart sensor circuits 120 include second, millisecond, and microsecond counters; however, in other embodiments, the clocks may include lesser or greater resolution.

At block 702, the primary microcontroller 528 increments a counter variable (C). At block 704, the primary microcontroller 528 starts an elapse timer. According to one embodiment, the elapse timer has microsecond scale resolution; however, in other embodiments, the resolution of the elapse timer may be configured differently.

At block 706, upon starting the elapse timer, the primary microcontroller 528 transmits a relatively short message (SetSecond) to a smart sensor circuit 120. The SetSecond message is configured to synchronize a second counter of the smart sensor circuit 120 to a second counter of the primary microcontroller 528. In one embodiment, where the primary microcontroller 528 utilizes the Modbus serial communication protocol to communicate with the smart sensor circuits 120 via the communication bus 122, the primary microcontroller 528 utilizes Function Code 6 of Modbus to transmit an eight byte "Write Single Register" command to the smart sensor circuit 120 that writes a single sixteen bit value to the smart sensor circuit 120.

In one embodiment, where the primary microcontroller 528 is transmitting the SetSecond message to the smart sensor circuit 120, the primary microcontroller 528 places the first byte of the SetSecond message in its transmit buffer. Once the entire first byte of the SetSecond message is transmitted to the smart sensor circuit 120 and the transmit buffer of the primary microcontroller 528 is empty, an interrupt service routine automatically sends the remaining bytes of the SetSecond message to the smart sensor circuit 120.

At block 708, the smart sensor circuit 120 receives the SetSecond message from the primary microcontroller 528. Once the smart sensor circuit 120 identifies a frame mark condition on the communication bus 122 (e.g., bus inactivity for 3.5 bits), the smart sensor circuit 120 recognizes that it has received the entire SetSecond message. At block 710, the smart sensor circuit 120 decodes the received SetSecond message and utilizes the decoded sixteen bit value to set its sixteen bit second counter. In other embodiments, the second counter may be of a different size (e.g., an eight bit or



thirty-two bit counter). Also, in other embodiments, different protocol types or sized signals may be used by the primary microcontroller 528 to set the second counter of a smart sensor circuit 120.

At block 712, the smart sensor circuit 120 replies to the SetSecond message from the primary microcontroller 528 that it has successfully received the SetSecond message. In one embodiment, the smart sensor circuit 120 places the first byte of the reply to the SetSecond message in its transmit buffer. Once the entire first byte of the replay is transmitted to the primary microcontroller 528 and the transmit buffer of the smart sensor circuit 120 is empty, an interrupt service routine automatically sends the remaining bytes of the reply to the SetSecond message to the primary microcontroller 528.

At block 714, the primary microcontroller 528 receives the reply to the SetSecond message from the smart sensor circuit 120. Once the primary microcontroller 528 identifies a frame mark condition on the communication bus 122 (e.g., bus inactivity for 3.5 bits), the primary microcontroller 528 recognizes that it has received the entire reply to the SetSecond message from the smart sensor circuit 120. At block 715, in response to recognizing that it has received the entire SetSecond reply from the smart sensor circuit 120, the primary microcontroller 528 stops the elapse timer and records the current value of the elapse timer. The recorded elapse timer value represents the total time that has elapsed since the SetSecond message was transmitted by the primary microcontroller 528 to the smart sensor circuit 120 and is indicative of the total Round Trip Time (RTT) required for a message to be transmitted from the primary microcontroller 528 to the smart sensor circuit 120 and for a reply to be returned to the primary microcontroller 528 from the smart sensor circuit 120.

As discussed above, the initial relatively short message (SetSecond) sent from the primary microcontroller 528 to the smart sensor circuit 120 is utilized for both RTT measurement and second counter configuration purposes. However, in another embodiment, the initial relatively short message sent from the primary microcontroller 528 to the smart sensor circuit 120 may only be used for RTT measurement purposes and not for counter configuration purposes.

At block 716, the primary microcontroller 528 determines if the counter variable (C) equals a predefined number of measurements (N). In response to a determination that the counter variable (C) does not equal the predefined number of measurements (N), at block 702 the counter variable (C) is incremented, at block 704 the elapse timer is reset and restarted, and at blocks 706-715 the primary microcontroller 528 calculates another RTT value, as discussed above.

At block 718, in response to a determination that the counter variable (C) equals the predefined number of measurements (N), the primary microcontroller 528 calculates a representative RTT value based on the previously calculated RTT values. For example, in one embodiment, the primary microcontroller 528 calculates a representative RTT value by calculating the median value of previously calculated RTT values. In other embodiments, the representative RTT value may be calculated differently (e.g., with an average RTT value, a maximum RTT value, etc.).

At block 720, the primary microcontroller 528 utilizes half of the representative RTT value as a clock offset to synchronize a millisecond counter of the smart sensor circuit to a millisecond counter of the primary microcontroller 528. The primary microcontroller 528 sets the millisecond counter of the smart sensor circuit to a value that corresponds to

a value of the millisecond counter of the primary microcontroller 528 but that is also adjusted to account for the time required for a message to pass from the primary microcontroller 528 to the smart sensor circuit 120 (i.e., the millisecond time of the primary microcontroller 528 plus half of the representative RTT). At block 722, the primary microcontroller 528 utilizes half of the representative RTT value as a clock offset to synchronize a microsecond counter of the smart sensor circuit to a microsecond counter of the primary microcontroller 528. The primary microcontroller 528 sets the microsecond counter of the smart sensor circuit to a value that corresponds to a value of the microsecond counter of the primary microcontroller 528 but that is also adjusted to account for the time required for a message to pass from the primary microcontroller 528 to the smart sensor circuit 120 (i.e., the microsecond time of the primary microcontroller 528 plus half of the representative RTT).

For example, in one embodiment, where a fourteen bit millisecond counter is utilized by the smart sensor circuit 120, the primary microcontroller 528 first utilizes Function Code 6 of Modbus to transmit a "Write Single Register" command to the smart sensor circuit 120 that writes a single ten bit value (corresponding to the value of the primary microcontroller's millisecond counter adjusted by half of the representative RTT) to the smart sensor circuit 120. The smart sensor circuit 120 utilizes the ten bit value received from the primary microcontroller 528 to set the first ten bits of its millisecond counter.

The primary microcontroller 528 then utilizes Function Code 6 of Modbus to transmit a "Write Single Register" command to the smart sensor circuit 120 that writes a four bit value and a ten bit value to the smart sensor circuit 120. The smart sensor circuit 120 utilizes the four bit value to set the lower nibble of its millisecond counter to a value adjusted by half of the representative RTT (as discussed above) and utilizes the ten bit value to set its microsecond counter to a value corresponding to the value of the primary microcontroller's microsecond counter adjusted by half of the representative RTT. Accordingly, the combined twenty bits of the smart sensor circuit's 120 millisecond and microsecond counters are synchronized with the millisecond and microsecond counters of the primary microcontroller 528 to account for transmission latency in the communication bus 122.

As described above, two messages are used to set the combined twenty-four bits of the smart sensor circuit's millisecond and microsecond counters as Modbus Function Code 6 messages may only transmit single sixteen bit words. However, in other embodiments, more or less than two messages may be utilized to set the counters of a smart sensor circuit. Also, the messages used to set the counters of a smart sensor circuit may be of any appropriate size and/or type protocol. Additionally, the counters of the smart sensor circuit 120 and/or the primary microcontroller 528 may be configured differently or be of any appropriate size.

The primary microcontroller 528 may repeat the clock synchronization process described above (with regard to FIG. 7) over multiple synchronization cycles to maintain accurate synchronization between the clock of the primary microcontroller 528 and the clock of the smart sensor circuit 120. The primary microcontroller 528 may also utilize the synchronization process described above (with regard to FIG. 7) to individually synchronize the clocks of any number of smart sensor circuits 120 within the load center 100 to the clock of the primary microcontroller 528 to account for latency in the communication bus 122.



In one embodiment, by utilizing the primary microcontroller **528** to initiate and control clock synchronization of the smart sensor circuits **120** and the primary microcontroller **528** to account for transmission latency in the communication bus **122** (e.g., an RS-485 communication bus) as discussed above, the clocks of the smart sensor circuits **120** and the clock of the primary microcontroller **528** may be synchronized to less than 0.1 millisecond of each other. This may ensure accurate synchronization between voltage measurements made by the primary microcontroller **528** and current measurements made by the smart sensor circuits **120**.

According to one embodiment, in addition to adjusting the clocks of the smart sensor circuits **120** to account for transmission latency over the communication bus **122**, the primary microcontroller **528** may also adjust the elapse timer to compensate for smart sensor circuit clock skew. Clock skew occurs when the clock of a smart sensor circuit **120** consistently runs either faster or slower than the clock of the primary microcontroller **528**. In one embodiment, the primary microcontroller **528** performs an adaptive algorithm that periodically adds or subtracts a correction factor to/from the elapse timer. The correction factor is iteratively calculated by measuring the skew of the smart sensor circuit clock (i.e., the difference between the smart sensor circuit clock and the clock of the primary controller **538**) at successive clock synchronization cycles. The correction factor is tuned until a minimum skew is achieved. In one embodiment, the correction factor has a microsecond scale; however, in other embodiments, the correction factor may be of any other scale.

In another embodiment, in addition to calculating a representative RTT as discussed above, the primary microcontroller **528** may utilize interrupt service routines (e.g., at the end of a SetSecond message transmitted by the primary microcontroller **528** or at the end of a SetSecond replay transmitted by a smart sensor circuit **120**, as discussed above) with known latencies to further define the representative RTT. For example, if the primary microcontroller **528** recognizes that the actual calculated latency of an interrupt service routine is longer than a predetermined latency for the interrupt service routine, the primary microcontroller **528** may use the difference between the actual latency and the predetermined latency to adjust the clock of a smart sensor circuit **120** to account for the additional latency within the system.

Even though examples in accordance with the present invention are described herein with reference to a load center, other examples may be utilized within any electrical system in which current, power and energy of a power line are desired to be monitored. It also is to be appreciated that examples in accordance with the present invention may be utilized to monitor any type (e.g., commercial or residential) or size system.

As described above, the synchronization process (e.g., as seen in FIG. 7) is utilized within a load center to synchronize the clocks of smart sensor circuits to the clock of a concentrator; however, in other embodiments, the synchronization process may be utilized to synchronize the clocks of any other types of devices which are coupled together via a multi-drop bus.

As described above, the synchronization process is implemented over a communication bus utilizing the Modbus serial communication protocol; however, in other embodiments, the synchronization process may be utilized with any

multi-drop bus implementing Modbus, Fieldbus, Profibus, or any other Multidrop master-slave protocol using a deterministic hardware network.

Even though examples in accordance with the present invention are described herein as utilizing a current transformer **114** capable of being clamped onto a circuit branch **102**, other examples may utilize a different type of current sensor. For example, current sensors utilizing shunt resistance, hall-effect, and toroidal (solid core) current transformers may be used.

By including only a single communication bus within a load center, rather than individual dedicated connections (e.g., "hub and spoke wiring"), and connecting all smart CT's to a CT concentrator within the load center via the single communication bus; a relatively small, less complex and more manageable method and system for utilizing a plurality of CT's to monitor circuit branches of a load center is provided. Also, by utilizing the CT concentrator to initiate and control clock synchronization of the smart CT's and to account for transmission latency in the communication bus, as discussed above, the clocks of the smart CT's and the clock of the CT concentrator may be synchronized to less than 0.1 millisecond of each other. As each smart CT is interrupt driven and in communication with the CT concentrator via the same communication bus (i.e., utilizing the same communication protocol), the smart CT's are able to respond quickly to the CT concentrator and have substantially the same transmission latency for messages from the CT concentrator.

Having thus described several aspects of at least one embodiment of this invention, it is to be appreciated various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of this disclosure, and are intended to be within the spirit and scope of the invention. Accordingly, the foregoing description and drawings are by way of example only.

What is claimed is:

1. A system for monitoring a plurality of circuit branches coupled to an input line, the system comprising:
  - a communication bus;
  - a controller having a primary clock with a first clock value, the controller configured to be coupled to the communication bus and the input line and further configured to sample voltage on the input line based on the first clock value;
  - a plurality of sensor circuits, each sensor circuit having a secondary clock with a second clock value and each sensor circuit configured to be coupled to the communication bus and at least one of the plurality of circuit branches, wherein each sensor circuit is further configured to sample current in the at least one of the plurality of circuit branches based on the second clock value; and
 wherein the controller is further configured to initiate, via the communication bus, synchronization of at least one secondary clock and the primary clock, and to synchronize, via the communication bus, the at least one secondary clock and the primary clock to account for transmission latency in the communication bus,
  - wherein in synchronizing the at least one secondary clock and the primary clock, the controller is further configured to:
    - calculate at least one Return Trip Time (RTT) from the controller to at least one of the plurality of sensor circuits having the at least one secondary clock; and



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transmit at least one synchronization signal from the controller to the at least one of the plurality of sensor circuits to adjust the second clock value of the at least one secondary clock based on the at least one RTT.

2. The system of claim 1, wherein the controller is further configured to utilize a multi-drop master-slave communication protocol to communicate with the plurality of sensor circuits via the communication bus.

3. The system of claim 1, wherein in initiating synchronization of the at least one secondary clock and the primary clock, the controller is further configured to transmit a measurement signal to the at least one of the plurality of sensor circuits having the at least one secondary clock, and to start a timer having an elapsed time value upon transmitting the measurement signal.

4. The system of claim 3, wherein the at least one of the plurality of sensor circuits is further configured to receive the measurement signal and transmit a response to the measurement signal to the controller.

5. The system of claim 4, wherein the at least one of the plurality of sensor circuits is further configured to adjust the second clock value of the at least one secondary clock based on the measurement signal.

6. The system of claim 4, wherein in calculating the at least one RTT from the controller to the at least one of the plurality of sensor circuits, the controller is further configured to receive the response to the measurement signal from the at least one of the plurality of sensor circuits, to stop the timer in response to receiving the response to the measurement signal, and to calculate the at least one RTT based on the elapsed time value of the timer.

7. The system of claim 6, wherein the controller is further configured to calculate a representative RTT based on the at least one RTT.

8. The system of claim 7, wherein the representative RTT is one of a median RTT, mean RTT, and maximum RTT.

9. The system of claim 7, wherein in transmitting the at least one synchronization signal from the controller to the at least one of the plurality of sensor circuits, the controller is further configured to transmit a first synchronization signal based on the representative RTT to the at least one of the plurality of sensor circuits, and wherein the at least one of the plurality of sensor circuits is further configured to adjust the second clock value of the at least one secondary clock based on the first synchronization signal.

10. The system of claim 9, wherein the at least one of the plurality of sensor circuits is further configured to adjust a millisecond counter of the at least one secondary clock based on the first synchronization signal.

11. The system of claim 9, wherein the controller is further configured to transmit a second synchronization signal based on the representative RTT to the at least one of the plurality of sensor circuits, and wherein the at least one of the plurality of sensor circuits is further configured to adjust the second clock value based on the second synchronization signal.

12. The system of claim 11, wherein the at least one of the plurality of sensor circuits is further configured to adjust a microsecond counter of the at least one secondary clock based on the second synchronization signal.

13. The system of claim 1, wherein the controller is further configured to synchronize, via the communication bus, current sampling performed by the plurality of sensor circuits with the voltage sampling performed by the controller.

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14. A method for monitoring a plurality of circuit branches coupled to a power line, the method comprising: coupling a controller to the communication bus and to the power line, the controller having a primary clock with a first clock value;

coupling a sensor circuit to each one of the plurality of circuit branches and to a communication bus, each sensor circuit having a secondary clock with a second clock value;

sampling, with at least one of the sensor circuits, current in at least one of the plurality of circuit branches based on the second clock value;

sampling, with the controller, voltage on the power line based on the first clock value; and

synchronizing, with the controller via the communication bus, the at least one secondary clock and the primary clock to account for transmission latency in the communication bus,

wherein synchronizing the at least one secondary clock and the primary clock includes:

calculating at least one RTT from the controller to at least one sensor circuit having the at least one secondary clock; and

transmitting at least one synchronization signal from the controller to the at least one sensor circuit to adjust the second clock value of the secondary clock of the at least one sensor circuit based on the at least one RTT.

15. The method of claim 14, wherein calculating at least one RTT includes:

transmitting a measurement signal from the controller to the at least one sensor circuit;

in response to transmitting the measurement signal, starting a timer of the controller having an elapsed time value;

receiving, with the at least one sensor circuit, the measurement signal;

transmitting, in response to receiving the measurement signal, a response to the measurement signal from the at least one sensor circuit to the controller;

receiving, with the controller, the response to the measurement signal;

stopping, in response to receiving the response to the measurement signal, the timer of the controller; and

calculating the at least one RTT based on the elapsed time value of the timer.

16. The method of claim 15, further comprising calculating a representative RTT based on a plurality of RTT calculations, and wherein transmitting at least one synchronization signal from the controller to the at least one sensor circuit includes transmitting at least one synchronization signal from the controller to the at least one sensor circuit to adjust the second clock value of the at least one sensor circuit based on the representative RTT.

17. The method of claim 14, further comprising synchronizing, with the controller via the communication bus, current sampling performed by the plurality of sensor circuits with the voltage sampling performed by the controller.

18. The method of claim 14, wherein transmitting at least one synchronization signal from the controller to the at least one sensor circuit to adjust the second clock value of the at least one sensor circuit based on the at least one RTT includes utilizing a multi-drop master-slave communication protocol to transmit the at least one synchronization signal from the controller to the at least one sensor circuit.

19. A system for monitoring a plurality of circuit branches coupled to an input line, the system comprising:



a communication bus;  
a controller having a primary clock having a first clock  
value, the controller configured to be coupled to the  
communication bus and the input line and further  
configured to sample voltage on the input line based on 5  
the first clock value;  
a plurality of sensor circuits, each sensor circuit having a  
secondary clock with a second clock value and each  
sensor circuit configured to be coupled to the commu-  
nication bus and at least one of the plurality of circuit 10  
branches, wherein each sensor circuit is further con-  
figured to sample current in the at least one of the  
plurality of circuit branches based on the second clock  
value; and  
means for calculating at least one RTT from the controller 15  
to at least one of the plurality of sensor circuits having  
the at least one secondary clock, and for synchronizing,  
with the controller via the communication bus, the  
secondary clock of the at least one of the plurality of  
sensor circuits and the primary clock of the controller 20  
to within 0.1 millisecond based on the at least one RTT.

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